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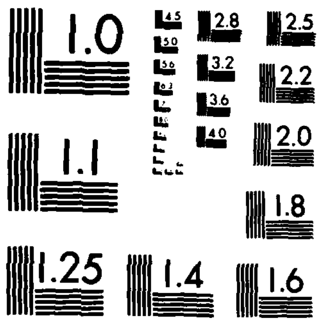

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This report summarizes this research effort in unsteady aerodynamics and aeroelasticity. Principal research results are listed and a cumulative list of technical reports and papers is provided.

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Publications and Related Activities

For the five years of Stanford's research activity under this grant, it is believed that the most significant "products" are the substantial number of publications and the advanced graduate students whose theses formed the foundations of those publications. Nearly all of these students are now constructively employed in academia, industry or government laboratories. Their names are recorded as authors or coauthors of Stanford SUDAAR reports, archival papers, etc.

At the beginning of the attached List of References, the Principal Investigator has attempted, in roughly chronological order, a comprehensive list of all such papers whose contents were wholly or partially supported by the grant. The format of the present report is to discuss this list in terms of areas of investigation. Then some more detail will be given on recent progress since the May 1983 distribution of the last Interim Scientific Report.

It is worth noting that almost all of these documents had their public origin in a seminar, an invited address, or an oral presentation at a technical symposium. Therefore several appeared first in the collected "Proceedings" or bound volume of papers from a meeting such as the AIAA/ASME Structures, Structural Dynamics and Materials Conference. Incidentally, many papers on fluid mechanics/aerodynamics find their way to the programs of the "SDM Conferences" through their relevance to fields like aeroelasticity and structu... loads.

In all such cases, it is the intent to get ultimate archival publication in Journal of Aircraft, AIAA Journal or another suitable AIAA or ASME monthly or quarterly. Because this process has built-in delays, several of the papers remain today at the "Proceedings" stage but will ultimately achieve the more permanent status. Indeed, the Principal Investigator is currently taking steps to persuade AIAA to accelerate the publication process in one or two cases. Unusually long time lags have been encountered during the last two years.

Summary of Research Prior to Mid-1983

Research and publication activity prior to about May 1983 has been covered fairly thoroughly in a series of Interim Scientific Reports, of which Ref. 13 was the latest. There were several general themes, most of which involved the determination of aerodynamic loads that might prove useful in the analysis of aeroelastic stability and response. In the earlier years, however, some genuinely aeroelastic work was supported, wherein the structural dynamic component predominated.

Aerodynamics, vibrations and flutter of vertical-axis wind turbines and related energy-conversion devices were investigated by Dr. F. Nitzsche. The emphasis was on setting up and solving the state-vector differential equations of a rotating beam-rod curved into the zero-bending-moment shape known as Troposkien. Especially novel were the transfer-matrix approach used to treat eigenvalue problems and discoveries such as the very large unfavorable influence of Coriolis forces on aeroelastic stability. In addition to Nitzsche's dissertation, publications supported in part by the present grant are Refs. 6 and 10.

The Principal Investigator devoted considerable effort to a particular question in the theory of nonlinear, unsteady transonic potential flows. This had to do with selecting the "optimum" combination of approximate partial differential equation, Cp-relation and kinematic boundary condition. It was done in the context of the unsteady flow produced by expansive withdrawal or compressive penetration by a piston in a 1-D channel containing perfect gas. The results – regarded as interesting but not conclusive – were published in Ref. 12.

Reference 12 also contains a progress report on work, done in collaboration with W. N. Boyd & W. S. Rowe of Boeing Commercial Airplane Co., on subsonic unsteady airloads of lifting surfaces. This concerns the practical extension of proven tools for calculating airloads and generalized forces on 3-D wings in simple harmonic motion to predict transfer functions of the Laplace-transform variable s throughout the entire area of the s-plane. Such transfer functions are the first essential step for adapting this and related theories to the design of active control systems for alleviating response to turbulence, reducing structural damage due to repeated loads and improving flutter performance. Some large military/civilian transport aircraft in the proposal stage already point to the use of such active technology as a way of achieving both higher speeds and better fuel efficiency.

As a result of this effort, optimal forms for the kernel function of the problem have been determined. The paper by Rowe & Cunningham (Ref. 11) and a very recent one by Desmarais (Ref. 14) were strongly influenced by these findings. A computer code embodying the best results, among them the excellent approximations described in Ref. 14, is in the process of being made generally available by Boeing and NASA.

A major experimental and theoretical examination of chordwise aerodynamic forces on oscillating lifting surfaces was completed in 1982 by Dr. J. K. Nathman. Under NASA and earlier AFOSR/AFFDL support, several 2-D oscillating airfoil models and a high-fidelity excitation system were constructed for use in the Stanford 0.5-meter subsonic wind tunnel (e.g., Ref. 3), Nathman's model was supported in such a way as accurately to measure both the chordwise and lift-type force components due to various combinations of pitching and plunging. The extensive data and analysis appear in Ref. 5 and, more comprehensively, in his thesis portion of Ref. 7.

Analytical and experimental calculations of the forces on two-dimensional airfoils are presented. It is shown that a slight amount of oscillatory camber has beneficial effects in increasing thrust and reducing the likelihood of stall. For 2-D wings there is a simple approximate relationship between the optimal thrust and efficiency which other researchers have shown applies in 3-D. To compare theory with experiment it was necessary to derive the effect of the wind-tunnel walls, which is shown to be quite significant in the case of the thrust force for small wind-tunnel height to wing chord ratios.

In general the experiment appears highly successful in that it was the first to measure the unsteady chordwise aerodynamics at higher reduced frequencies. The force phases are measured with resolutions better than a degree. A trend which seems to indicate that unsteady viscous effects are small is that the mean suction and the second-harmonic agree very closely with potential theory. This is despite the fact that unsteady *skin friction* is expected to increase the drag. The amplitude data show only small dependence on reduced frequency. The phase angles, however, are more frequency-dependent and follow the theory closely. In all comparisons, the theory with tunnel walls included proves more accurate. A panel-theory method was also developed in order to test the hypothesis that thickness effects increase both lift and suction relative to what would be expected on a thin airfoil.

Finally, there was begun in 1981 an investigation of wind-tunnel boundary effects in unsteady flow, with emphasis on their relevance to the type of flutter and airload testing which is so important to safety of large aircraft. A thorough literature search was completed on boundary effects predicted for wings oscillating in a subcritical airstream and on the more difficult questions of how these effects may be dealt with or "canceled out" in transonic flow. Relative to the transonic case, nothing of a classical theoretical nature – as opposed to applications of computational fluid dynamics (C.F.D.) codes – had been published concerning even two-dimensional unsteady flow. Yet, in the range of reduced frequencies most significant for primary aeroelastic stability and response, transonic wall influence will be equally as pronounced as in the steady flow case. Partial-chord shocks on two-dimensional and three-dimensional wings may or may not extend out as far as the tunnel boundaries. In either event there is known to be a significant influence (completely overlooked by linearized theory) on flutter of angle-of-attack and profile shape.

Ph. D. candidate Becker van Niekerk worked on the transonic problem until his temporary departure from Stanford in January 1982. His potentially most important idea was a "loudspeaker" concept. This attempts the cancellation of the influence of slotted or perforated walls on the unsteady portion of loading on an oscillating wing. It has a qualitative analogy with the steady-flow wall cancellation scheme first proposed by Ferri, Sears, et al. (Refs. 15, 16, 17). van Niekerk returned in 1984 and has developed other interests. Whether research will be completed on the transonic question is difficult to say at the present writing, but it is of course too late for support under AFOSR 79-0061.

The study of subcritical wall effects has constituted a major focus during 1983 and 1984. It is reviewed in more detailed by a subsequent section.

Summary of Recent Research in 1983 and 1984.

Efforts have consisted first of some preliminary examination of the dynamics and aerodynamics of high-performance aircraft, executing maneuvers involving extreme excursions in angle of attack. That study resulted in the award of a new grant, on which concentrated work began in April 1984. Two other subjects received major study: compressible flow about lifting surfaces moving in a spiral path and the aforementioned unsteady, subcritical wall effects. Progress on these up to late 1983 was reviewed in Sections 1B and 1, respectively, of Ref. 18.

The spiral lifting-surface research has as its objective an improved theory for steady or unsteady linearized, compressible loading and flow about a propeller or rotor. An advance over conventional blade-element models, it addresses the true small-perturbation *boundary-value problem* in a manner analogous to lifting-line or lifting-surface theory for planar wings. The governing P. D. E. of potential theory is expressed in a coordinate system with origin fixed at the center of rotation and with the $r-\theta$ axes spinning with the propeller at its angular rate ω. Only a few prior investigations have chosen this frame of reference (e. g., Johansson, Ref. 19, Davidson, Ref. 20), which is quite logical because it converts the basic problem into one of steady flow.

Both unsteady and steady versions of the P. D. E. for the perturbation potential have been derived and examined. One novel feature, which comes from a study of the characteristic surfaces and is obvious physically, is that for a subsonic flight speed there is a cylinder within which the flow is locally subsonic surrounded by an unbounded region of supersonic flow with real, curved Mach waves. (Davidson avoided dealing with the latter by analyzing the propeller in a wind tunnel of closed, circular cross section.) For the steady case, the potential can be broken into an "incompressible" part which describes the spiral wake for downstream, plus a correction portion dependent on Mach No. which takes care of boundary conditions (B. C.) at the propeller.

Both portions of the potential have been represented by suitable series of separated solutions of the P. D. E. In a sort of lifting-line approximation, the flow tangency B. C. at the propeller is satisfied by a collocation procedure. Steady-flow solutions have already been calculated and appear reasonable. The plan is to publish a paper shortly on this steady part. Then the Ph. D. dissertation by Ms. V. Wells will be issued, and subsequent literature will describe both the steady and unsteady cases. Applications of the latter to prediction of aeroelastic stability are contemplated.

The research on prediction of 3-D wind-tunnel boundary effects on oscillatory wing airloads has recently moved into a phase of program writing and numerical applications. It proved infeasible to carry out the planned modifications to the existing free-air computer program RHO-IV. Therefore, an entirely new program has been written and verified, which has as its goal the calculation of generalized-force matrices for arbitrary small wing motions, reduced frequency of oscillation, and subsonic flow Mach number. The results can be directly compared with oscillatory pressure/airload data or combined with another structural-dynamic program to carry out flutter analyses.

In the new program are now kernel-function adjustments to account for various forms of wind-tunnel walls. Currently, only the solid wall and open walls have been implemented. However, provisions have also been programmed to handle mixed boundary types.

These various boundary types offer the user the option of reducing the amount of computation required based on the model/tunnel description. For example, it may be sufficient to use a semi-infinite tunnel when looking at a small wing mounted on a side wall. This offers a reduction in computation to $2\sqrt{n}$ image kernel evaluations, where n is the number of images required to simulate four walls. These boundaries are simulated using image patterns rather than specialization of the kernel function. Thus, as more efficient forms of the image kernel are implemented, the basic patterns possible will remain unaffected.

Some preliminary numerical results have already been generated for purposes of validating the program. For example, pitch damping derivatives were calculated to compare with theory and data from Garner, et al. (Ref. 21). In the process, a free-air lift-curve slope of 3.475 per radian was estimated for their straight-tapered wing of aspect ratio 4.3. This is essentially a quasi-steady derivative because of reduced frequency of 0.02 was assumed. The value of 3.8 is a better estimate, but satisfactorily close in recognition of the small number (12) of collocation points used with RHO-IV.

A parallel search has been carried out for flutter and oscillatory-air-load measurements in the literature, notably those where wall effects are believed to be significant. At least a dozen promising examples are known. The indications are sufficiently strong to raise questions about the safety of flutter clearance of some new aircraft designs based on tunnel tests at high subsonic speeds.

Two distinct but related phenomena can be encountered. Discrete resonant frequencies can be estimated by solving a 2-D wave equation in the tunnel cross section. The effective sound velocity is $a_\infty\sqrt{1-M^2}$, where a_∞ refers to the subsonic free stream of Mach No. M. When the crossflow acoustic mode can interact with vibration of a centered wing, the predicted airloads have at least a logarithmic singularity. In Lee, a student of the Principal Investigator, is currently implementing a program from Southwest Research Institute (Ref. 22), which calculates these 2-D modes and frequencies for essentially arbitrary tunnel cross-sectional shapes. This code assists calculations in other than rectangular geometry – for instance, the octagonal configuration of Transonic Dynamics Tunnel, NASA Langley Research Center (TDT).

For three dimensions, the only flutter test program in which a resonant influence was clearly identified and discussed was that on a simplified 1/17th-scale model of the U.S. SST in the TDT. (Ruhlin, et al., Ref. 23.) As the flutter frequency passed, with increasing tunnel Mach number, near the estimated lowest critical value for closed walls, a remarkable and unexpected drop in flutter dynamic pressure was observed in three test points.

There also exists another case (Farmer and Hanson, Ref. 24), where the same phenomenon may have occurred with a pair of large-aspect-ratio swept wings in the TDT. These were two models of essentially identical geometrical, inertial and elastic properties. With regard to the measured transonic "dips" in their flutter speeds, a 20% difference in minimum critical dynamic pressure was attributed to differences between the wing thickness distributions. It is hypothesized that the "dips" may also be affected by tunnel "resonance." The plan is to follow up this presumption with flutter calculations based on data supplied by the authors.

As for the future, the research on flutter effects and realization of the 3-D oscillatory program are the work of USAF Capt. Lanson Hudson, who is now assigned as a faculty member at Air Force Institute of Technology. Captain Hudson is confident that he will complete the investigation and thereby earn the Stanford doctorate within six months to a year. The resulting publications will, of course, acknowledge the support of AFOSR under the subject grant.

Mr. Lee is remaining at Stanford and has recently passed the Qualifying Exam, permitting him to work for the Ph. D. in Aeronautics and Astronautics. His future research on tunnel resonance prediction will be funded by a grant from NASA Langley Research Center. He has already made progress toward idealizing the complex boundary conditions associated with slotted or perforated walls, surrounded by a pressurized plenum chamber. It is expected that his work will be finished by mid-1985. As in the case of Capt. Hudson, his publications will recognize the preliminary support provided under Grant AFOSR 79-0061.

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Publication and Reports from Grant AFOSR 79-0061

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Sincerely yours

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